APPENDICES

APPENDIX A

EFFECTS ON ELEMENTS OF THE ENVIRONMENT DUE TO VIBROSEIS® SURVEY OPERATIONS

Conclusions from studies, reports and interoffice memos kindly supplied by the International Association of Geophysical Contractors strongly suggest that the pulsating inputs of energy to the earth's surface which are the basis of the Vibroseis® principle cause no damage to structures or wells if certain offsetting distances are observed. Nuisance to human beings may be regarded as slight to moderate, depending upon the receptor and distance from vibration source.

Duvall and Fogelson[1] did a statistical analysis of the data collected by several experimenters. They came to the conclusion that particle velocity was the physical quantity most indicative of the resulting damage. They also concluded that 2.0 inches per second of particle velocity was a reasonable threshold between the "safe" zone and the "damage" zone. Other authors indicate that 4.0 inches per second is the threshold and define a caution zone between 2.0 and 4.0 inches per second in which minor damage may occur. Recent evidence from the study of the long wavetrain energy indicates that the caution zone should start at 1.0 inches per second or slightly below. Most authors define "damage" as minor plaster cracks or further opening of existing cracks.

In a study which evaluated both nuisance to humans and damage potential resulting from vibrator vehicles, the following summary table was developed by a Vancouver, B.C. engineering consultant.

Table 1

Vibration Equipment*	Distance (Feet)	Peak Particle Velocity (Inches per Second)
April 27, 1977		
1 Vibrator Unit	50	.08
	50	.07
	50	.11
April 28, 1977		
4 Vibrator Units	25	.36
	25	.40
	25	.57
	50	.30
	50	.20
	50	.19

* Vehicle weights not given

Source: R. M. Hardy and Associates, Ltd., written communication to Thurston Consultants, Ltd., (both of Vancouver, B.C.)

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1 Duvall, W. I. and Fogelson, D. E., "Review of Criteria for Estimating Damage to Residences from Blasting Vibrations", Bureau of Mines Report, RI 5968, (1962).

The table shows that a considerable increase in the peak particle velocity occurs by adding the additional vibrator units. The study corroborated the Duvall and Fogelson conclusion (mentioned previously) by saying, "Peak particle velocity is considered the best measure of damage potential from vibration and it is generally accepted in the industry that a peak particle velocity of 2.0 inches (5 centimeters) per second is a reasonable and safe limit below which damage to buildings is not expected. The safe criteria is well documented in the literature and is a conservative figure to preclude damage to structures."

Hardy and Associates noted that most human perception of damage levels are made from an empirical standpoint: "The average person can feel vibrations that are from 1/100 to 1/1000 part of the magnitude necessary to damage structures. In addition, human response to vibrations is determined by sight and sound, such as window rattling, as well as feeling. It can be appreciated that such disturbances perceptible to hearing, sight and feeling, particularly if they are unexpected, exert a profound influence in a decision that the source is objectionable even though the magnitude of such disturbances is acceptable from the point of view of safety and discomfort." No recommendations regarding minimum distances from Vibroseis® units were made.

Conoco conducted an experiment in Kings County, California using two vibrator units with regard to possible damage to water wells near vibratory surveyances. This experiment demonstrated that the peak particle velocities measured by the instrumentation was roughly equivalent to freight trains operating on the Santa Fe railroad mainline 100 feet from the pickup sensor. Another correlation made in the experiment suggests that Vibroseis® operations are comparable to and no worse than excavating equipment. In terms of nuisance to humans, the experiment noted that a reasonable "threshold of feeling related to earth movements is about .023 inches per second but added that the threshold could vary from three times greater (.067 inches/second) to three times below (.007 inches/second). A "human variability factor" was defined as occurring at approximately .054 inches/second of movement. (All of the above values are at least 5 times lower than the 2.0 inches/second standard) The report pointed out "that the vibration level at which the average person thinks damage will result is considerably below the actual damaging level observed." As a result of the experiment, a minimal clearance from structures and irrigation facilities of 50 feet was recommended (P.L. Wilson, written communication, date unknown).

In another study initiated by Conoco, peak particle velocities were calculated for various sources of vibration in a city environment. Representative readings from the data are compared in Table 1. For purposes of assessing a nuisance factor, common vibrations were also measured. See Table 2.

The study concluded by suggesting that inhabitants of buildings approximately 20 to 40 feet from the vibrator have greater psychological disturbances from Vibroseis® vibrations than from other agitation sources normal to the city environment. (Albert Hrabetz, interoffice memorandum, "Comparative Vibration Levels from Various Sources of Agitation" July 31, 1958.) From the data presented in the three examples above, it appears that 100 feet separation between buildings or wells and a Vibroseis® survey team, would preclude damage to those structures and provide distance for an additional margin of safety.

Table 2 Comparison of Representative Readings from Two Vibratory Tests

Particle Velocity (inches per second)	Source	Distance in feet, source to sensor
2.0	Industry standard for minimum level of minor damage	
.6000	4-ton vibrator	25
.1130	4-ton vibrator	100
.0561	Door slam, wood floor	2
.0280	4-ton vibrator	150

Particle Velocity (inches per second)	Source	Distance in feet, source to sensor
2.0	Industry standard for minimum level of minor damage	
.6000	4-ton vibrator	25
.2300	4-ton vibrator	50
.1130	4-ton vibrator	100
.0280	4-ton vibrator	150
.000963	4-ton vibrator	800

Table 3 Common Vibrations

Particle Velocity (inches per second)	Source	Distance in feet, source to sensor
.0561	Door slam, wood floor	2
.0445	Door slam, wood floor	
.0199	Garbage disposal, grinding small bones	3
.0133	Attic fan	12
.004	Passenger car	20
.00261	Pickup truck	30
.0009	Washing machine - wash cycle	5

APPENDIX B

EXPLOSIVES

HANDLING

For a number of years, the traditional energy source for seismic prospecting was dynamite; it was the only source which provided enough energy for the recording equipment in use at that time. Dynamite and other high explosives produce a very fast build up in pressure when detonated and thus are an excellent seismic source. Detonation speed of high explosives may vary from 4,000 to 23,000 ft/second, depending upon strength and grade. An example of a high explosive formulated for seismic work is Geogel®.

Some drawbacks to the use of high explosives are immediately apparent:

- Shot holes must be drilled, which may be difficult and expensive in some areas. In rough terrain, truck-mounted drill rigs cannot be moved easily, while transporting water for drilling purposes in arid areas increases costs.

- Dynamite handling is dangerous. Nitroglycerin, the main constituent of dynamite, becomes unstable with age. Restrictions placed on dynamite use in some states has caused inconvenience and extra expense.

It is not surprising that as early as 1972, 46 percent of land shots in the United States were from nondynamite sources. (Dobrin, 1972).

Blasting agents are not explosives as such, but can be made to detonate by using a primer or blasting cap. Blasting agents are formulated from ammonium nitrate and do not require the stringent precautions required for high explosives.

The handling, transportation and use of explosives in Washington are governed by Chapter 70.74 RCW, Washington State Explosives Act; Chapter 296.52 WAC, Safety Standards for the Possession and Handling of Explosives; and applicable Department of Labor and Industries rules and regulations.

PREDICTING DAMAGES FROM SEISMIC DETONATION[1]

In the discussion in Appendix A, it was suggested that measurement of particle velocity was a useful parameter to predict damages from ground movement. Through research conducted by the E.I. duPont de Nemours Company and aquatic biologists, a relationship between weight of explosive charge and distance required to maintain a peak particle velocity at two inches per second, or less,

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1 Written communication from E.I. duPont de Nemours Co. to Ferrante Construction, Valdez, AK; August 10 1977.

was derived.[2] The following quantity-distance chart shows the weight of explosives which may be fired in a single blast without detrimental effects on aquatic life.

Distance (feet)	Maximum Charge Weight (pounds)*
20	2.4
40	9.6
60	21.5
80	38.4
100	60.0
120	86.4
160	153.6
200	240.0
240	345.6
280	470.4
320	619.4

* To prevent damages to nearby property and structures through excessive pressure rises, modern blasting technique has adapted the practice of spacing portions of blasts with small but significant delays measured in milliseconds. The pressure rise curve is more gentle as a result. The values of maximum charge weight shown are per delay, in this case eight milliseconds. Shot-hole seismic charges are not large enough to require use of the sequential technique.

In the derivation, a conservative value of two inches per second particle velocity was used to minimize impacts to anadromous fish embryos.

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[2] The relationship considers the following parameters:

a. Acoustic impedances and densities of water and rock,

b. Velocity of sound in water,

c. Compressional wave velocity in rock, and

d. Blast pressures in water and rock.

APPENDIX C

The following material was reprinted from the Forest Land Management Program Final Environmental Impact Statement published by the Washington State Department of Natural Resources in November, 1983. (Figures and tables are not included.)

EXISTING ENVIRONMENTAL CONDITIONS

PHYSICAL EFFECTS

EARTH

Geology

"Geology" is here defined to mean earth materials found on the earth's surface and the natural processes that have acted or now act on them. "Soil" is not included in this discussion. Geologic materials can have a wide range of composition, degree of formation and distribution within regional or local areas. Geology in any one locale results from the geologic history of that area, which could cover thousands to hundreds of millions of years of erosion, deposition, tectonic movement, glaciation or volcanic activity.

Rocks in northeastern Washington are over 500 million years old. The glacial deposits that overlie them in places are only 13,000 years old, and ash from Cascade volcanoes deposited over rocks and glacial debris may be only 2,000 to 6,000 years old. Modification of the state's geology is a continuing process as the earth's surface is eroded and the resulting sediments are deposited to form new geologic strata. A geologic timetable (Figure 26) has been provided for perspective.

It is convenient to divide Washington into seven physiographic provinces, shown on Figure 27: (1) the Olympic Peninsula Province, (2) the Willapa Hills Province, (3) the Glaciated Puget Sound Lowland Province, (4) the Cascade Mountain Range Province, (5) the Okanogan Highlands Province, (6) the Blue Mountains Province, and (7) the Columbia Basin Province.

Each province has its own unique combination of geological and other environmental characteristics. In many cases, boundaries between provinces are gradual transitions, with a mix of certain features at the boundaries.

The Olympic Peninsula Province includes the core of the Olympic Mountain Range, its foothills and the surrounding lowlands that were not covered by continental glaciation. The Willapa Hills Province includes the area generally bounded by the Chehalis River to the north, the Columbia River to the south, the Cowlitz River to the east and the Pacific Ocean to the west. The Black Hills are also included in the Willapa Hills Province. The Glaciated Puget Sound Lowland Province consists of all those lowland areas surrounding Puget Sound where continental glaciation has played a primary role in influencing soil characteristics and behavior.

The Cascade Mountain Range Province is bounded on its northeast corner by the Methow River Valley, considered part of the adjoining Okanogan Highlands Province. Further south, the eastern boundary of the Cascade Mountain Range Province is the easternmost extension of managed timberland on the Cascade foothills. The Okanogan Highlands Province contains the part of Okanogan County from the Methow Valley east as well as all of Ferry, Stevens and Pend Oreille Counties and a small part of northern Spokane County. The Blue Mountains Province includes the Blue Mountains and the surrounding foothills. The Columbia Basin Province includes the generally nonforested areas of lower elevation in Eastern Washington outside the limits of the Cascade Mountain Range Province, the Okanogan Highlands Province and the Blue Mountains Province.

Because department-managed forest lands include relatively small blocks of land spread throughout the state, it is more practical to summarize the geology and geological conditions for each province than to try to describe department-managed lands. The following briefly summarizes the geology found in each province. For more detailed information, see "Geology of Washington," Reprint 12, published by the department's Division of Geology and Earth Resources (DNR, 1978), and the Geologic Map of Washington by Huntting et al., 1961.

The Olympic Peninsula Province

Two major bedrock terrains make up the Olympic Peninsula: peripheral rocks and core rocks. The oldest peripheral rocks are sandstone, argillite and conglomerate, which underlie and intermix with middle (and possibly lower) Eocene basaltic volcanic rocks (the Crescent Formation). The outcrop belt of the Crescent Formation forms a large horseshoe pattern open on the west. The Crescent is overlain by fossiliferous Eocene through Miocene sedimentary rocks of mostly marine origin. All peripheral rocks are folded and faulted, but they are, in general, in continuous layers. In contrast, the rocks in the core are highly deformed, although they also range from middle (and possible early) Eocene to middle Miocene.

The oldest rocks of the peninsula are exposed only at Point of the Arches on the coast. On sea cliffs and sea stacks, metamorphosed and altered Jurassic or older igneous rock is overlain by probable pre-Tertiary basalts and sedimentary rocks. The whole complex is covered by Eocene sedimentary rocks.

The youngest rocks of the peninsula are sedimentary rocks which formed in a marine environment, the Pliocene Quinault Formation and the Pliocene Quillaute Formation. They crop out only on the west of the peninsula.

Glacial debris from continental ice sheets surrounds the mountains on the northwest, north, east and southeast. Many mountain valleys and most of the lowland on the west are flooded with gravels from Olympic alpine glaciers. Moraines of Olympic glaciers dot the higher slopes and valleys as well. Quaternary wave-cut terraces due to sea-level fluctuations during the Pleistocene occur along the western coastal margin of the province. Landslides, particularly debris flows, occur on the steep slopes throughout the Olympic Peninsula.

The Willapa Hills Province

Willapa Hills Province is made up of Tertiary marine sedimentary rock with layers of volcanics that increase in amounts of nonmarine strata as the Province moves east. Thick Quaternary sands and gravels that were deposited by streams flowing from glaciers overlay many areas. The Crescent Formation basalts core the higher hills in the south and west and northeast parts of the Willapa Hills Province. The Cowlitz Formation (interbedded marine and nonmarine siltstones and sandstones with occasional basalt flows) lies west of Chehalis/Centralia and along the northeast slopes of the basalt core of the Willapa Hills in the west and south-central area of the province.

The Lincoln Creek Formation -- a band of basaltic sandstones and tufaceous siltstones that crop out south of Aberdeen -- continues south and east of Pe Ell and Toledo. This formation borders the Cowlitz Formation on the east and north. It also crops out in the northeast corner of the province west of Oakville. In the southeast corner of the province, Columbia River basalt flows cap the sediments north and east of Longview. Surrounding much of the basalt core of the Willapa Hills are Miocene to Pliocene fluvial, lacustrine, brackish-water and shallow-marine sediments.

The early Pleistocene Logan Hill Formation was deposited by streams flowing from glaciers and forms some flat-topped surfaces on the very eastern edge of the province. This iron-stained, interbedded gravel, sand and silty clay is found at about 300 to 400 feet elevation. Stream terraces of Pleistocene age found along the valley sides of the Cowlitz River are silt and fine sand rising 60 to 80 feet above sea level. At the western margin, Quaternary terrace deposits cover the Tertiary bedrock, extending from Grays Harbor nearly to the Columbia River. Quaternary terraces from outwash of the continental glaciers are found along the Chehalis River, and Quaternary landslide deposits cover much of the landscape where the tufaceous Tertiary sediments have had massive slope failures.

The Glaciated Puget Sound Lowland Province

The Glaciated Puget Sound Lowland is a north-south depression filled with Pleistocene glacial and nonglacial sediments. Continental glaciers have occupied the Puget Lowland as many as four times. The surface of the Puget Lowland is covered predominantly by drift left by the latest glacier to occupy the Puget Lowland -- about 15,000 years ago. Soils have developed on till, outwash, sands and gravels and lacustrine silt and clay surficial deposits. The drift covers almost the entire lowland except in the northern and central areas, where relatively small amounts of bedrock are exposed. An extension of the Cascade Mountain Range occupies part of the northern Glaciated Puget Sound Province. The San Juan Islands and Chuckanut Mountains are Paleozoic to

Mesozoic crystalline, metamorphic and sedimentary rock that have been scoured by the continental glaciers, leaving exposed rock outcrops and areas of thin drift overlying bedrock. In the San Juan Islands, the Turtleback complex is a grouping of metamorphic, sedimentary and igneous rock types and younger sedimentary sandstones and shales. To the east, the Chuckanut Mountains consists of the continental, coal-bearing Chuckanut Formation to the north and a metamorphosed sedimentary rock type to the south, overlain in places by glacial deposits. In the central Puget Lowland, sedimentary rocks crop out in places where not covered by drift along another structural rise in a northwest trend from North Bend to Seattle. West of Bremerton, the basaltic Green and Gold Mountains rise to elevations of 1,000 to 1,700 feet and are covered by glacial deposits where erosion has not exposed the bedrock.

The most recent deposits found in the Glaciated Puget Sound Province are Holocene alluvium in the river and stream valleys, beach deposits along the shore of Puget Sound and landslide deposits (see Erosion) found predominantly at the base of the cliffs along Puget Sound.

The Cascade Mountain Range Province

The structure of Washington's Cascade Mountain Range is like an arch whose axis of folding is tilted or plunges to the south. Hence, like a plunging arch, the strongly uplifted and deeply eroded northern end of the range exposes the oldest rocks. These rocks are either recrystallized (metamorphic) from having once subsided into deep realms of high temperature and pressure, or are associated younger, once-molten igneous intrusive bodies (batholiths) which are themselves coarsely crystalline igneous and metamorphic rocks. They are relatively resistant to erosion and tend to persist as the steepest and tallest clusters (massifs) of peaks.

The larger intrusive bodies illustrate the different rates of erosion well, and include such units as: Mount Stuart, carved from granitic rocks of the Mount Stuart batholith; many alpine summits north of Snoqualmie Pass, eroded from the Snoqualmie batholith; the base of Mount Index and neighboring peaks, cut into the granitic rocks of the Index batholith; Sloan, Del Campo, Gothic and Kyes Peaks of the Monte Cristo Group, sculptured in granite; granitic peaks of the Illabot Range (Snow King Mountain and Mount Buckindy); the Dome Peak massif, chiseled from a granitic intrusive; the Chilliwack Group, sculptured from granitic rocks just south of the Canadian border, and the red granitic peaks of the Mount Silver Star area, carved from the Golden Horn batholith.

Crystalline metamorphic rocks notable for their resistance include banded types such as those of the Cascade Pass area (Mt. Goode, Mt. Buckner, Boston Peak, Forbidden Peak, Sahale Peak and Eldorado Peak are spectacular examples) and the rugged massifs of the Picket Range north of the Skagit River. These peaks are carved largely from one of the most strongly metamorphosed rock units, the Skagit gneiss.

Earlier deformation of the Cascades has produced a northwest-trending alignment of geologic structural features across the region. The latest major uplift established most of the altitude and the north-south trend of the range in

Pliocene time, but the northwest-trending structural alignment has been re-emphasized by certain features eroding more rapidly than others. Major valleys such as those of the Snoqualmie River, the Skykomish River, Lake Chelan, the upper Sauk River, the Suiattle River and the upper Yakima River have been eroded essentially parallel to the trends of adjacent structures. A notable down-faulted section preserves younger sedimentary rocks in a northwest-trending structure. Erosion by the Wenatchee drainage has carried away much of the younger, more easily eroded sedimentary rock, to reveal the older crystallines in steep faultline.

Sedimentary and volcanic rocks of late Cretaceous and Tertiary age have largely escaped the metamorphism that so thoroughly recrystallized the older rocks in earlier Mesazoic and Paleozoic time. Across most of the southern Cascades, where uplift was not strong enough to bring about deep erosion, the younger rocks still cover their ancient foundations.

Resistant ridge-forming sandstones interlayered with erodible siltstones and shales (called the Swauk Formation) swing in a horseshoe bend around the Mount Stuart massif, crossing Swauk Pass to form a belt northwest of the head of Cle Elum Lake. The Swauk Formation has been carved into foothills or relatively low mountains; again, the structural grain is clear in ridges and valleys eroded at different rates and times. The pattern of folds is perhaps not spectacular, but a great swarm of basaltic dikes*, the Teanaway dikes, adds diversity to the landscape.

Because of superior resistance to erosion, the dikes have come into relief, as can be seen along the highway across Swauk Pass, where they resemble dark walls rambling up and down hills of tawny Swauk Formation. The overlying Teanaway basalts have been largely removed by erosion, but in places they form steep rimrock cliffs above more gently contoured slopes of the Swauk Formation.

Throughout the southern Cascades the younger rocks are predominantly volcanics (solidified lavas and tephra, the airborne debris from volcanoes) of Tertiary age. Like the rocks to the north, their fold axes trend northwest and they are dislocated in places by faults. In spite of stream erosion, these volcanic rocks successfully cover most of the older rocks and structures upon which they were erupted. The harder units form steep cliffs and sharp ridges, particularly in the higher, glaciated portions of the range.

The rocks of the southern Cascades are also pierced locally by still younger intrusive bodies such as the Tatoosh pluton, the Carbon River stock and the Bumping Lake pluton. These are resistant granitic bodies exposed in the foundation and surroundings of Mount Rainier. Smaller intrusive plugs are of finer-grained volcanic rocks.

Younger Tertiary volcanic rocks include the Columbia River basalts of Miocene age, which spread not only across interior Washington but also over much of the ancestral southern Cascades, which had by this time been eroded to a low-lying

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*See Glossary

landscape. Proof of uplift in post-Miocene (i.e., Pliocene) time is graphically established by the obvious deformation of these originally horizontal lavas.

Columbia River basalts are essentially absent in the northern Cascades. A few small patches cap shoulders of sandstone, gneiss and granitic rocks above the river between Wenatchee and Entiat. Probably the north Cascades remained rugged enough in most places to remain above the lava floods; certainly they have been uplifted strongly enough to have shed any marginal basalt coverage they may once have acquired. The southern Cascades, on the other hand, received a larger cover of basalt in the first place, which they still largely retain because of their relatively modest uplift and incomplete erosion. In addition, lavas of Pleistocene and Recent age have followed canyons cut in the older rocks or been spread across the upland in places. These youngest flows are prominently in the far south near the latitude of Mt. St. Helens and Mt. Adams. They illustrate a continuing contest between upbuilding by volcanism and seemingly endless erosion in the southern Cascades.

As mentioned, Pleistocene glaciation and erosion have left scenic terrain throughout much of the Cascade Range; however, glacial drift is usually found only in the high-elevation cirque basins and larger valleys like the Skagit, Nooksack, Snoqualmie, Puyallup, Nisqually, Cowlitz and Lewis River valleys on the west side of the Cascades and the Chelan, Entiat, Wenatchee, Yakima and Naches River valleys on the eastside.

During the Quaternary period, development of picturesque volcanoes in the Cascade Mountains resulted in numerous deposits of tephra. Volcanic ash and ejecta from Mt. St. Helens, Mt. Adams and Mt. Rainier cover much of the terrain in the southern Cascades; in the northern Cascades ash and ejecta from Glacier Peak cover areas east into the Wenatchee, Entiat and Chelan Valleys. Erosion and mass wasting have added recent deposits of alluvium and landslide debris to the landscape.

The 1980 eruptions of Mt. St. Helens resulted in volcanic debris and mudflow deposits on some department-managed lands and tephra (volcanic debris, pumice, and ash) deposits on others. These deposits present a unique set of management problems, as described in earlier analyses.

The Okanogan Highlands Province

The Okanogan Highlands Province is a broad sweeping landscape in which summits and ridges curve smoothly down to glacially rounded valley floors. The geology is related to the Rocky Mountains to the east. Dominating the eastern Okanogan Highlands are rocks of well-layered marble, phyllite, quartzite, greenstones and gneiss, with scattered bodies of granite. The central and western highlands are predominantly granitics, with some metamorphics and volcanics east of the Okanogan River valley. The large block of department-managed forest lands west of Tonasket is predominantly granite and schist, with lesser areas of volcanic and metamorphic rocks. The Methow Valley has a thick, complicated sequence of sedimentary and volcanic rocks that crop out throughout the valley.

Probably the most important feature of the Okanogan Highlands Province is the scouring of bedrock and deposition of glacial sediments by continental ice sheets. Most of the mountain tops and high ridges were smoothed down by the continental glaciers that overran this area. Till was plastered on the hill slopes where soil had been eroded. As the glaciers receded, many kame (ice margin) and outwash terraces were formed in many of the valleys. These terraces -- layered and unlayered silts, sands and gravels, cling to the hill-sides at many elevations throughout the province. With recession of the glacier, stagnant ice dammed many rivers and streams forming lakes. The result is widely dispersed fine-grained lacustrine sediments on many hillslopes and valley bottoms.

During the Holocene epoch volcanic eruptions deposited ash from Glacier Peak, Mt. Baker, Mt. St. Helens and Mt. Mazama throughout the entire area. The ash, parent material and climate have formed unique soils in this province. Also during the Holocene, erosion played an important part in molding the landscape, particularly in areas of loose glacial deposits, where silt, sand, and gravel have been deposited and now make up the alluvial valley floors of the rivers and streams.

The Blue Mountains Province

Because of its marginal timber stands, the Blue Mountains Province is discussed very briefly. The predominant geologic feature of the Washington Blue Mountains is the heavily dissected Miocene basalt flows. These flows have been warped, and now river and stream erosion have cut deep canyons into the basalt. Because the climate is dry, little mass wasting (see Erosion) has occurred other than rockfalls along the steep canyon walls.

The Columbia Basin Province

The Columbia Basin Province is the nonforested area outside the Cascade Mountain Range Province to the west, the Okanogan Highlands Province to the north and the Blue Mountains Province to the south. The northeastern region of this province (near Spokane) is the only area likely to have any manageable timber. The entire province is underlain by a massive thickness of Miocene basalt flows, overlain in places by flood deposits of sand, silt and gravel from the great Pleistocene floods, or by loess, the probable wind-blown silt of Pleistocene age. In the northeastern part of the province, flood deposits cover most of the area, but outcrops of basalt occur along eroded flood channels. Flood deposits can consist of silts, sands or gravels in varying depths and stratification. In this area also are deposits of silt and clay lake sediments. Erosion has resulted in more recent deposits in the stream and river-valley bottoms. Volcanic ash from the Cascade volcanoes was the last material deposited over the area.

Soils

Soil is a fundamental and very important natural resource used in any forest management program. It is the basic medium for forest growth and rooting, and the storehouse of mineral nutrients and water required by the forest community.

"Soil" is defined as the earth material at or near the surface of the earth which supports or is capable of supporting plants. Its lower limit is the depth to which roots or the effects of other biological activity have penetrated.

Younger soils have many of the characteristics of the material from which they were formed. As time progresses, weathering alters the physical and chemical properties of the parent material, generally forming smaller soil particles and creating new chemical and mineralogical soil constituents. Water percolating downward through the soil can transport these soil constituents from one level and deposit them at a lower level. Thus, as a soil becomes more highly developed, a certain amount of layering is produced. These soil layers, called horizons, contrast with the soil materials above and below. The collection of soil horizons that makes up a soil is known as a soil profile.

At the surface of most undisturbed forest soil profiles is a layer of organic material known as duff. The duff layer consists of organic forest litter material, such as needles, twigs, cones and decomposition products. The duff layer grades into the mineral soil horizons below. This layer (the "O" horizon) contains 90 percent of the soil nutrients.

Mineral soil horizons can be divided into three categories. "A" horizons occur at or near the soil surface, and are the horizons into which surface organic matter first enters the mineral soil. "A" horizons are often the sites of the most intense biological and chemical activity in forest soils. "B" horizons occur at intermediate levels in soils, and often represent a zone of accumulated soil materials leached from the "A" horizon. At the lower limits of the soil profile are the "C" horizons, consisting of soil materials with relatively slight alterations of the parent materials due to surface weathering.

Among the most important soil-related properties affecting or affected by forest management activities are: (1) topography, (2) soil texture and rock-fragment content; (3) soil drainage characteristics; (4) the parent material from which the soil was derived; (5) soil depth and (6) amount, character and distribution of soil organic matter.

Topography -- gradient of slope, slope shape and position on slope -- significantly influences the character and behavior of soils. As a rule, soils formed on steeper slopes tend to be shallower and less developed than soils of the same area on more gentle topography. This is because, as slopes increase, the potential for soil removal by erosion and mass wasting increases (see Erosion). The slope gradient and its shape have a significant effect on water movement, both on the surface and internal. Concave surfaces tend to collect and retain more moisture than otherwise similar convex surfaces.

Position on slope can influence major soil properties. Soils generally become deeper and finer-textured as one moves down from ridgecrests to the toeslopes below. Three slope classes will be used to describe the gradient of topographic slope; moderate slopes are those less than 30 percent, steep slopes are those between 30 and 65 percent, and precipitous slopes are those greater than 65 percent.

Textural class of a soil is determined by relative proportions of clay, silt and sand. Percentages of gravel and other rock fragments are considered textural modifiers. Textural class of a soil has much to do with influencing moisture movements through and into it. Moisture movement through and into soils tends to be favored by coarse textures and restricted by fine textures. Erosion potential for a soil is influenced significantly by its texture (see Erosion).

The potential for a soil to absorb and hold nutrients and other chemical agents, natural and artificial, is increased as finer soil fractions, primarily clay, increase. Soil textures for particles less than two millimeters in diameter will be subdivided into three categories based on percentages of sand, silt and clay. Coarse-textured soils will include those with sand, loamy sand or sandy loam textures. Medium-textured soils will include those with loam, sandy clay loam, sandy clay or clay-loam textures. And fine-textured soils will include those with silt loam, silty clay loam, silty clay, silt or clay textures.

Soil drainage measures the rate at which moisture moves into and through the soil. Soils with adequate drainage can absorb and transport internally enough water to avoid problems caused by surface flow or saturation. Several factors influence soil drainage, including soil texture, soil structure, organic matter content, topography and depth of soil horizons restricting water movement.

Soil structure, the degree and type of aggregation of individual particles into larger units, affects porosity and thus soil drainage. Since organic matter serves as a major binding agent in forming soil structure and increasing soil porosity, it is also important in determining soil drainage. Changes in soil structure and soil organic matter content by certain forest management activities can alter a soils drainage behavior.

Variations in soil parent material can produce significant differences in soil properties and behavior in areas of uniform climate, vegetation, topography, etc. Certain parent materials increase the potential for erosion, mass wasting and other problems in the soils formed from them. As an example, sideslopes on soils from sedimentary rock types have been found generally less stable than those from igneous rock types in the same area. Knowing the parent material distribution in an area can thus indicate potential soil problem areas.

Soil depth greatly determines a soil's capacity to absorb and hold water, nutrients, etc. Shallow soils become water-saturated faster during precipitation, and saturated soils tend to be more subject to surface flow erosion and mass wasting. Shallow soils are those that average less than 20 inches deep to bedrock or other impermeable layer; moderately deep soils average from 20 to 40 inches in depth; and deep soils average 40 inches or more in depth.

Organic matter significantly affects soil character and behavior. It serves as a primary binding agent in creating and maintaining soil structure. Soil structure has a major effect on maintaining good soil porosity. Soils with much incorporated organic matter tend to have greater structural development, are more porous and are thus more resistant to surface flow and its erosion. The binding action of incorporated soil organic matter also reduces erosion by holding particles in place and limiting detachability.

A soil is the product of interaction of: (1) climate, (2) organisms, (3) parent material, (4) topography and (5) time. A variation in any one can produce significant differences in soil properties and behavior. The wide range of climate, vegetation, geological materials, topography and soil ages across the forest lands of Washington produces an extremely varied collection of soil types. The physiographic provinces described earlier will be used here to aid the discussion of soil conditions.

The Olympic Peninsula Province

The Olympic Peninsula Province is characterized by high mean annual precipitation and soils with generally shallow to moderate depths. Mean annual precipitation ranges from approximately 80 inches along the western coastal areas to over 200 inches at the central core of the Olympic Range. The shallow to moderate soil depths have been greatly influenced by a combination of glacial activity centered in the Olympic Range, the character of the geologic parent material and recent geomorphologic processes.

The central core of the Olympic Range was the source of several glacial events during the Pleistocene period. Glaciers extended out beyond the mountain front, scouring and depositing as they went. Within the mountain range, U-shaped valleys with steep to precipitous sideslopes are a typical result of this glaciation. Rapid stream downcutting has also contributed to oversteepening of slopes in certain areas. The steep to precipitous sideslopes, high precipitation rates and somewhat unstable character of the primarily sedimentary bedrock within the range interior have contributed to a relatively high natural slope instability. This has resulted in mostly shallow soils on the sideslopes. Along the larger stream bottoms and beyond the mountain front, alluvial and glacially derived deposits generally support soils of greater depth.

Textural properties of Peninsula soils span the full range. Soil textures within the mountain front tend to be generally coarser, due to the relative youth of the soil surfaces. Gravel contents tend to be relatively high, particularly on steep to precipitous sideslopes. Beyond the mountain front, textures become generally moderate to fine, due to the somewhat finer character of the geologic parent material and the greater age of most of the soil surfaces.

Organic matter content and distribution within the soils of the Peninsula is primarily a function of elevation. At lower elevations the organic matter in the duff layer is more rapidly converted into humus and incorporated into the mineral soil than at higher elevations. There, where temperatures are colder, soil biological activity tends to be significantly reduced. Thus, at higher elevations forested soils tend to have thicker duff layers and lower humus production and incorporation. Lower humus incorporation limits soils' structural development and forest productivity.

Forest productivity is lower at higher elevations in the Olympic Peninsula Province because of shallow soils, lower humus production and incorporation, and shorter, cooler growing seasons. As one moves out through the Olympic foothills to the coastal areas, forest productivity becomes significantly greater because of improved soil, higher temperatures and a longer growing season.

The Willapa Hills Province

The Willapa Hills Province has much less topographic relief than the Olympic Peninsula Province to the north. The Province was not subjected to scouring by glaciation during the Pleistocene period; its absence has produced a region largely covered by relatively mature surfaces and soils. The long time during which soil-forming processes have been active, and their intensity due to the high mean annual precipitation (generally from 70 to 120 inches) and moderate temperatures, have produced an area characterized by deep, medium-to-fine textured soils.

Drainage characteristics of most soils in this province are favored by their depth, good structural development and relatively high organic matter. In undisturbed situations, most soils of the Willapa Hills Province can absorb and transport all water supplied during peak precipitation with minimum surface flow or other negative effects. The poorly drained soils in the Province generally occur in depressions or on level surfaces with drainage-restricting soil horizons.

Although surface flow is minimal and general drainage characteristics favorable on most undisturbed soils in the Province, mass wasting is a problem in certain areas. Deeply weathered sedimentary materials, particularly those with strata that concentrate subsurface water and those on steep to precipitous sideslopes, tend to favor mass wasting. Soil surfaces formed on basalts in the Province, as well as other parts of the state, tend to be relatively free of most mass wasting processes.

Organic matter contents in most soils of the Province are high in comparison to other Washington areas. High precipitation and moderate temperatures favor production of large amounts of forest litter (needles, twigs, cones, etc.), which is rapidly converted into humus and incorporated into the soil. Rapid conversion of litter into humus favors these soils' structural development and nutrient status. The "A" horizons are generally thicker than those in other parts of the state.

Soils of the Province are among the most productive in the state. The greater depths, finer textures, better structural development, higher humus contents and better drainage of these soils compared to those of other provinces contribute to this greater productivity.

<u>The Glaciated Puget Sound Lowland Province</u>

Soils of the Glaciated Puget Sound Lowland Province are in a region of relatively subdued topography with moderate mean annual precipitation levels generally between 30 and 70 inches. Soils of this region vary widely because of the variety of glacial and more-recent parent materials deposited here. Due to the relative youth of most soils in the region (less than 13,000 years for most) characteristics of the parent materials have been little altered by soil-forming processes. Thus, parent material is of primary importance in determining these soils' characteristics and behavior. Three major types of glacial deposits support forested soils in this province: glacial till, glacial outwash and glacial lacustrine.

Till is deposited directly by glacial ice, and thus lacks the particle-size sorting characteristic of water-deposited parent materials. Till soils can contain a wide range of particle sizes, from large stones to clay, within the same profile. The till-derived soils of the Glaciated Puget Sound Lowland Province generally have an extremely resistant layer of compacted till material at a depth of from 20 to 40 inches, which limits penetration of both roots and water.

In certain areas shallow layers of till have been deposited directly on the underlying bedrock. These soils behave much as other till soils of the region, in that the bedrock also restricts penetration of roots and water. Till soils present forest management problems in certain situations. As the depth to the impermeable layer becomes shallower, soil saturation is more likely to cause mass wasting and surface flow, particularly on steep sideslopes. In low-lying depressions the impenetrable layer can limit drainage and thus increase the chances of surface saturation, particularly during the rainy season.

Glacial-outwash deposits are primarily sand and gravel-sized particles much more sorted and stratified than till deposits. Because of their generally moderate slopes, coarser textures and lack of restrictive layers, outwash soils tend to have the lowest potential for mass wasting and erosion of any of the glacially-derived soils.

Soils from glacial lacustrine deposits are the finest textured in the region. The textures are dominated by silts and clays deposited in glacial lakes. These lacustrine deposits often display layering, with bands of contrasting texture. Their fine textures and the banding, which tends to concentrate subsurface water to saturation levels, greatly limit the drainage. Soils formed on lacustrine deposits present a great potential for erosion and mass wasting particularly on steep and precipitous slopes. The soils' generally restricted drainage can cause accumulations of surface water in low-lying depressions, particularly during the rainy season.

Humus production and incorporation occur at average rates throughout the Glaciated Puget Sound Lowland Province because of the moderate climate. Production and incorporation are hampered in certain soils by limited water-holding capacity or excessive moisture. Thin "A" horizons are typical in the province. Forest productivity of these soils is generally average for Western Washington. The highest productivity in this region is generally found on deep, well-drained soils of medium texture. Coarse-textured outwash soils with a lot of gravel, and poorly drained fine-textured lacustrine soils, are of below-average productivity.

The Cascade Mountain Range Province

The Cascade Mountain Range Province is perhaps the most diverse. Variations in elevation, precipitation, parent material, topography and vegetation contribute to a wide range of soils in this province.

Soil depths generally vary with elevation and slope. Soils at higher elevations and those on precipitous slopes tend to be shallow, while deep and moderately deep soils occur commonly on moderate slopes and at lower elevations. In many areas of the province, especially in the northern sections, glaciation and natural erosion and mass wasting have left large areas of exposed bedrock and shallow soils. These soils, as in other parts of the state, have a higher potential for mass wasting and erosion, particularly on steep slopes. In the southern parts of the province are large areas of deep and moderately deep soils formed on a variety of parent materials, including volcanic-ash deposits and deeply weathered bedrock.

Because of the predominant coarse and moderate soil textures in the Cascade Mountain Range Province, its major drainage is caused by topography and depth to an impenetrable layer. Soil drainage in this as in other provinces often presents problems in areas of concave slope shape, where surface and subsurface waters accumulate. Shallow soils exaggerate the hazards of surface flow and mass wasting.

Organic matter character and distribution in forest soils of the Province follow the pattern common to other forested mountain regions. Organic matter is converted to humus and incorporated into the soil more slowly under the low temperatures of the higher-elevation forests. Duff layers generally get thicker and humus production is reduced as one moves higher in these forested areas.

The rain-shadow effect of the Cascades has created a drier forested environment on their eastern slopes, complete with a different set of forested communities and soil-forming processes. The drier forests of Eastern Washington generally contain less organic litter and less moisture for leaching and other soil-forming processes. Compared to soils on the western Cascade slopes at similar elevations in similar parent material, soils on the eastern slopes are generally less weathered and less acid, and have less organic matter.

Forest productivity varies widely. Areas of deep, medium-textured soils and favorable climate in the southwest corner of the Province provide above-average conditions for forest growth. Forest productivity is limited by shallow coarse-textured soils occurring throughout the province, the short growing season of the high elevations and the low precipitation of the eastern forested flanks of the Cascades.

Deposits from the 1980 eruptions of Mt. St. Helens present a new set of soil characteristics on some department-managed lands. Lack of soil development on these deposits and their high erodibility produce serious forest management problems. Forest productivity cannot be accurately determined, but it is generally accepted that current forest productivity levels are below those before the eruption, particularly on mudflow deposits and deeper volcanic ash and pumice deposits. The high mass wasting and surface erosion on these deposits may require special forest management plans.

The Okanogan Highlands Province

The Okanogan Highlands Province, like the Cascades to the west, contains a wide range of environments and soils. Located in the rain shadow of the Cascades, its mean annual precipitation averages approximately 15 inches at the lower elevations along the western and southern boundaries and rises to above 50 inches in the mountainous areas of Pend Oreille County. Elevation within this province has a great effect on mean annual precipitation, forest communities and soils. As elevation increases within the province, mean annual precipitation increases, stocking densities of the forest communities generally increase and more moisture is available for soil-forming processes.

The province has been extensively glaciated. Glacial outwash and till deposits are the predominant soil parent materials; glacial lacustrine deposits are also common in some areas. Wind-deposited soil materials, predominantly silt, and volcanic-ash deposits blanket much of the province and overlie these glacial deposits. Because of the resistant character of bedrock materials and the rugged topography in certain areas, a significant proportion of the area was left with shallow soils and bedrock after the glaciers retreated.

Because of relatively slow soil formation and relative youth of these soils, their textures have been little altered since the parent materials were deposited. Coarse- and medium-textured soils are typical, and gravel contents, particularly in outwash and till soils, are generally high.

Soil drainage is not generally a problem in the province during the dry season, except on shallow soils or in depressions. During the spring snowmelt, however, particularly when surface soil horizons are frozen, the water added is more than many soils can absorb. This can cause surface flow, ponding and associated problems. This situation can occur throughout the other forested regions of Eastern Washington as well.

As in the other forested regions of Eastern Washington, soil organic matter is relatively low in the Okanogan Highlands Province, reflecting the low mean annual precipitation of much of the area. Organic matter increases as elevation and mean annual precipitation increase. It reaches a maximum in the northeast corner of the province, where forest and precipitation conditions are similar to those in Western Washington.

Throughout Eastern Washington there are often contrasts between the vegetation and soils of north- and south-facing slopes. Because of protection from more vegetation, thicker duff layers and the binding effects of more soil organic matter, soils on north-facing slopes tend to be more stable than nearby soils on south-facing slopes.

The Blue Mountains Province

The Blue Mountains Province has climatic characteristics similar to those of the Okanogan Highlands Province, but with slightly lower maximum mean annual precipitation at higher elevations. The province is underlain primarily by basalts. Glacial deposits of basaltic material are found at the higher elevations, while wind-deposited parent materials (loess) become common at the lower elevations. Evidence of volcanic ashfall materials is common in many soils of the province.

Despite differences in parent materials, soil-forming processes and forest soil management problems in the Blue Mountains Province are similar to those in other parts of Eastern Washington.

Forest productivity is relatively low throughout the province, and tends to be limited by low precipitation at lower elevations and low temperatures at high elevations. Soil characteristics generally do not limit forest productivity.

The Columbia Basin Province

The Columbia Basin Province is the generally nonforested lower-elevation area of Eastern Washington not included within the other provinces. Its soils range from deep, fertile silt-loam soils formed on loess in the southeastern corner of the province to the very gravelly glacial outwash soils in the central part of the province. The few forests in this province are generally at its edges in areas of slightly higher mean annual precipitation or where topography creates northern aspects and soil-moisture conditions favor tree survival. Soil characteristics have less influence on forest productivity in this province than mean annual precipitation and topographic position. Drainage, water erosion, and mass wasting are generally not considered problems in the forested areas of the Province because of the generally coarse-textured, stable soils on the typical subdued topography. The limited forest management in this province has small negative impact on soils because of their stable character and the low mean annual precipitation.

Topography

Same as Geology.

Unique Physical Features

Washington is an area of great topographic diversity; some of this diversity appears on the widely scattered department-managed forest lands. Difficulties in attempting to catalog these features (for example, the "Environmental Reconnaissance Inventory" of the U.S. Army Corps of Engineers in 1973) are compounded by the checkerboard location of that forest land.

An illustration of this problem (relatively small tracts and large features) is provided by the so-called "Channeled Scablands" of Eastern Washington. Here, catastrophic late Pleistocene floods left extensive channel systems and related features. An isolated tract of state timber land might exhibit only one side of a single meltwater channel. The segment of rock wall that forms the channel edge would probably be unrecognizable as such from the ground, would have miles of counterparts elsewhere and would not in itself (out of context) appear unique.

Another difficulty in inventorying unique features has to do with defining "unique." Using the common definition of "being without like or equal," it is easy to see that, given enough scrutiny, all physical features are unique. One waterfall or volcanic cinder cone may look pretty much like another to the untrained eye, but the expert can often point out important characteristics that make it unique.

Problems of scale, setting, perspective and observer training and background aside, the approach to unique physical features used here is to identify the kinds of features one can expect in various parts of the state, and thus possibly on department-managed timber lands. An acquaintance with the geology and geologic history of the physiographic provinces can assist in understanding the distribution, history and significance of such features.

Erosion

"Erosion" is defined as the process of detachment and transportation of soil materials by water, gravity, glacial ice and wind. On most forested lands the effects of glacial ice and wind erosion are negligible. In some areas of Eastern Washington wind is erosive because of the sparse vegetation under the trees. Erosive forces acting on forested areas are moving water (water erosion) and gravity (mass movements).

Water erosion requires three conditions: (1) surface flow, (2) detachability and (3) transport. Surface flow occurs when the water reaching a soil surface exceeds soil infiltration rate. Surface flow is most common during high intensity rainfall. Several factors influence infiltration rate. The role of coarse textures, good soil structural development, low bulk densities and undisturbed duff layers in favoring rapid infiltration was discussed in Soils.

When soils are saturated from long rainfall or when the amount of rainfall exceeds infiltration rates, nearly all the precipitation may become surface runoff. Because of the many irregularities of the ground surface, overland flow in mountainous areas is quickly concentrated into tiny streams (rills) where its erosive power is greatly increased. Large changes in velocity of flow are caused by slope differences. Flow velocities affected by slope alone vary as its square root. For example, an increase of four times slope will double the velocity of a given flow volume.

The detachment ability of surface flow varies as the square of the velocity (Longwell, Knopf and Flint, 1939). Small abrasive particles in surface flow greatly increase its power to detach other particles.

Soil removed from rills and gullies is usually determined by flowing surface water, but splashing raindrops usually detach most of that which is eroded from smooth surfaces (Ellison, 1947). Undisturbed duff limits soil detachability by reducing raindrop impact and favoring infiltration.

Several soil properties influence its potential for detachability. Middleton (1930) found texture a general indicator of erodibility. He found that where ratio of clay to silt in a soil is very low, too little clay is present to bind the material into aggregates, and silt particles are free to be suspended in the runoff water. Musgrave (1947) studied soils from 19 localities and found that silt loams were most erodible, sandy soils least. Olson and Wischmeier (1963) concluded that coarse sandy soils were least erodible, soils whose characteristics were dominated by clay were moderately erodible and soils of intermediate texture were most erodible.